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Investigating Lateral Boundary Forcing of Weather Research and Forecasting (WRF) Model Forecasts for Artillery Mission Support

by Andre Pattantyus and Robert Dumais, Jr., Mentor

ARL-MR-0835 **January 2013**

NOTICES

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Army Research Laboratory
White Sands Missile Range, NM 88005

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
January 2013	Final	June−Aug, 2012

4. TITLE AND SUBTITLE Investigating Lateral Boundary Forcing of Weather Research and Forecasting (WRF) Model Forecasts for Artillery Mission Support	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Andre Pattantyus and Robert Dumais, Jr., Mentor	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRL-CIE-M White Sands Missile Range, NM 88005	**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-MR-0835
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Accuracy of global numerical weather prediction (NWP) models is highly dependent on initial atmospheric conditions and to a lesser extent on physical parameterizations. Generally, model error grows as a result of poor initial conditions. Limited area models (LAMs) have an additional source of error/variability from their lateral boundaries, forced from global models or other LAMs. Lateral boundary forcing can be a substantial source of error/variability for LAMs due to interpolation of coarse atmospheric data down to fine grids and high-resolution topography. Domain size has been identified as a way to control the ‘spatial spin-up’ and internal variability of LAMs caused by lateral boundary conditions (LBCs). Previous research has found that larger LAM domains provide additional freedom for the model to create its own solution, whereas smaller domains are dominated by the forcing from the lateral boundaries. U.S. Army artillery uses LAM output to correct trajectories from ‘standard atmosphere’ conditions to those of the current atmosphere. Sensitivity testing to the Weather Research and Forecasting model’s LBCs over Europe is performed herein. Initial results from limited cases suggest modest difference between large and small domain experiments, except that the magnitude of error is a function of domain size.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Robert Dumais, Jr.
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UU	20	**19b. TELEPHONE NUMBER** (*Include area code*)
Unclassified	Unclassified	Unclassified			(575) 678-4650

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18Contents

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Acknowledgments

I would like to acknowledge the mentorship of Robert Dumais, Jr. for his great supervision and valuable insight during analysis of results. Valuable feedback was also provided by Pat Haines and James Cogan. James Cogan provided computational code to produce artillery meteorological messages, which was essential to this work. Technical support was provided by Robert Flanigan. Thanks also to the rest of the U.S. Army Research Laboratory (ARL) staff at White Sands Missile Range (WSMR) for a pleasant working environment and making me feel welcome for the summer internship once again.

Student Biography

Andre Pattantyus received his Bachelor of Science in Meteorology from Plymouth State University, NH in 2007. He received his Master of Science in Meteorology from Florida Institute of Technology in 2010. His Master's Thesis titled Numerical Investigations of Mountain Flows in the Las Vegas and Owens Valleys involved high-resolution mesoscale modeling using the Weather Research and Forecasting Advanced Research WRF (WRF-ARW). In June 2011, Andre was the lead author of "Improving High-Resolution Model Forecasts of Downslope Winds in the Las Vegas Valley" that was published in the Journal of Applied Meteorology and Climatology. This paper was the result of his Master's Thesis research. He presented this research at the Florida Academy of Sciences Annual Meeting in March 2010, the 5th International Symposium on Computational Wind Engineering in May 2010, the International symposium for the Advancement of Boundary Layer Remote Sensing in June 2010, and the American Meteorological Society (AMS) Annual Meeting in January 2011. In the summer of 2011, Andre participated in the Science and Engineering Apprentice Program (SEAP) at White Sands Missile Range (WSMR) where he was involved in research with WRF-ARW and four-dimensional data assimilation (FDDA). Andre is currently in the Meteorology Ph.D program at University of Hawaii at Manoa and continues to research the use of the WRF-ARW at high-spatial resolution over complex terrain and the use of FDDA and 3-Dimensional Variational data assimilation (3DVAR). He is especially interested in assimilated radial winds from NEXRAD radar. Other interests include the use of the WRF-ARW and FDDA for short-term cycling forecasts for wind farms. He plans to pursue a career in applications meteorology and mesoscale modeling.

1. Introduction

The U.S. Army and Marine artillery use a mobile nowcast-prediction system to support field operations. This core system currently uses the National Center for Atmospheric Research (NCAR) Penn State Mesoscale Model 5 (MM5) numerical weather prediction (NWP) limited area model (LAM) down to a grid-spacing of 4 km. An upgraded version of the nowcast-prediction system has been requested by the Army with increased spatial resolution (grid spacing close to 1 km) and is slated to use the WRF-ARW, the follow on of the MM5. The requirement for higher spatial resolution may be that domain size be limited to minimize computation time.

The effects of domain size have been studied in detail for climate simulations using LAMs to determine the effects of lateral boundary conditions (LBCs) on model performance by measures, such as model accuracy and variability. LBCs are a unique and unavoidable aspect of LAMs that will continue to represent a significant limitation to their utility for any application (*1*). The LBCs are prescribed by global NWP models, other LAMs, or reanalysis datasets with coarse resolution. Errors can enter the LAM from LBCs that may themselves suffer from limited data, such as over the oceans. This error then propagates through the LAM negatively affecting the predictive skill of the LAM and even entirely negating the benefits of high-resolution and sophisticated physics (*1*). Situations that may provide substantial error sources include significant cross-boundary flow upwind of the LAM domain, extensive forcing (either physical or dynamical) near the boundaries, and inconsistent physical-process parameterizations (i.e., cumulus parameterization schemes).

The consensus of past research is that larger domains reduce error from lateral boundary conditions within LAMs. This finding is not sensitive to a specific LAM and is found in the Weather Research and Forecasting model (*2–4*), NCEP Eta Model (*5, 6*), Canadian Regional Climate Model (*7, 8*) (RCM), and Regional Climate Model 3 (*9*) (RegCM3). The following results also relate to domain size and LBCs. Experiments with WRF found domain size shows high sensitivity of the upper-level flow to domain size (*2*). It is best to avoid placing any domain over oceans or other regions lacking sufficient data (*3*). When larger domains are used in WRF there appeared to be a larger independence of the regional model compared with the driving data (*4*). This result is also found in the Eta model applied to air quality modeling (*5*), as well as the Canadian RCM (*8*), and RegCM for summertime precipitation studies (*10*). High sensitivity of the Eta model quality as a function of domain size is also found (*6*). Changes to the domain size may considerably alter the geographical distribution of the internal variability, such as the storm track or rainfall pattern (*8*).

Arguments have emerged for the use of small domains in certain cases as well. In a study using RegCM it was found that the smaller domain produced a closer fit to observed precipitation due to the interior solution being more closely constrained by the driving fields (observations) from the LBCs (*10*). This result is partly attributable to the quality of observed large-scale forcing fields. Smaller domains are more economical when the external field data is high quality (*6, 9*). When internal model processes become important (i.e., surface forcing) larger domains in which the model solution is more free to respond to variations in internal parameters (i.e., surface fluxes) is likely to be preferable (*10*). Similar results are found using Regional Atmospheric Modeling System (RAMS) as well (*11*).

This discussion of model freedom and variability introduces the concept of "spatial spin-up," analogous to temporal spin-up, an important consideration when choosing domain size. Systemic model underestimation of flow dependent variables seems to be a direct consequence of the fact that the flow must travel a characteristic distance from the lateral boundaries, the "spatial spin-up," prior to the small-scale features achieve a sufficient level of development (*7*). Underestimation of small-scale transient variance must be expected over a great part of small domains (*7*); however, this effect can be reduced when simulating over a region with strong orographic forcing or land/sea contrast that may enhance the skill of the regional climate model and correct some errors at small scales (*12, 13*).

Eliminating error from lateral boundary conditions can result in smaller errors within the interior model domain. Model output is used to account for current atmospheric conditions in calculating trajectories. In contrast, a "standard atmosphere" assumes zero wind and a density profile that decreases exponentially with height. In general, there are large differences between a standard atmosphere assumption and using forecast values that are as close to the actual conditions encountered by the artillery projectile. Therefore, it becomes necessary to test a range of domain sizes to determine the optimal configuration for the next generation of the artillery meteorological model. It is hypothesized that larger domain size will reduce LBC error and that small domains will be closer to the prescribed forcing data. Also, because the system is run at high-spatial resolution in a cycling nowcast environment, reducing the computation time is extremely important.

Sensitivity experiments were performed with the WRF-ARW over Meiningen, Germany for two strong wintertime extratropical cyclones. These cases were chosen intentionally because of strong forcing and flow across the region that would potentially create LBC error growth as mentioned earlier. The cases were cyclones Joachim (16 December 2011) and Andrea (5 January 2012). Each case was simulated three times with increasingly larger outer domains but with the innermost domains unchanged in size and position to isolate the effects of LBC error.

2. Experimental Design

Figure 1 displays the one-way triple-nested domain configurations in WRF-ARWv3.2.1 centered over Meiningen, Germany used for this study. The dimensions for the small parent domain (SM) are 121 × 121 (1080 km), the medium (MD) 171 × 171 (1530 km), and the large (LG) 221 × 221 (1980 km). Grid spacing is 9 km in the parent domain; 3 km in the intermediate domain (168 × 168), which covers central Germany; and 1 km in the innermost nest (109 × 109) over the Meiningen region. Vertical resolution is produced with 57 terrain-following vertical levels. The initial and LBCs are given by the 0.5° Global Forecast System (GFS) forecasts, which have an effective grid spacing of approximately 50 km.

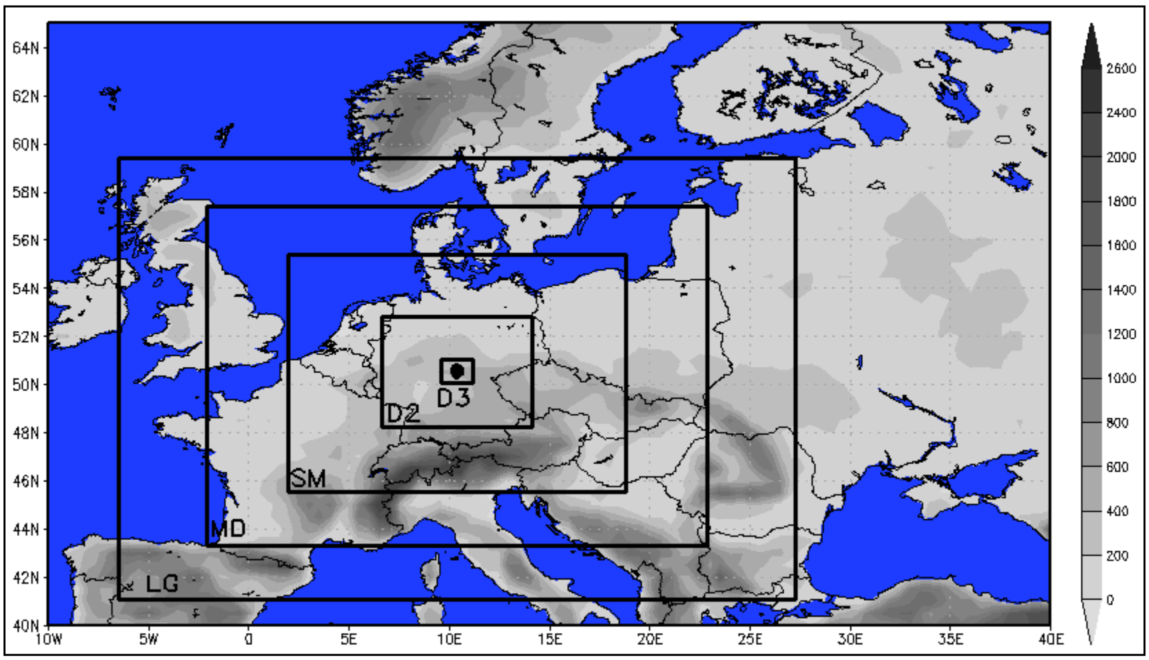

Figure 1. The three 9 km domains, LG, MD, SM, tested in this study along with the inner domains, D2 and D3, which remained stationary across all experiments. The circle in the middle of D3 represents the position of Meiningen, Germany. The shading represents the terrain (m).

All model physics are held constant to isolate the effects of LBC error. The quasi-normal-scale eliminate (QNSE) boundary-layer and surface-layer parameterizations are used to represent low-level turbulent mixing and surface heat and moisture fluxes, respectively. The NOAH land surface model is used to represent topographic and land use effects. Radiation is parameterized by the Dudhia and RRTM schemes for short-wave and long-wave radiation, respectively. Cloud microphysics are represented with the WRF Single-Moment 5-class scheme. The Kain−Fritsch cumulus parameterization is used in the 9 km domain only.

For both cases, Andrea and Joachim, simulations were started at 00 UTC and integrated for 24 h. Detailed analysis of these cases will focus on the 0−12 h forecasts, because this is the time period of interest most pertinent to U. S. Army and Marine artillery; however, results for the entire 24 h period will also be presented. Unfortunately, because the model is run in a ”cold start” mode there will be a period of 0−6 h where it is ”spinning-up.”

Results from WRF are compared against GFS 0.5° analyses to determine the error resulting from LBCs. Also, the GFS forecasts used for initial conditions and LBCs will be compared against the GFS analysis to give a baseline for the error growth. The area of consideration will be confined to the limits of the smallest parent domain. The error is calculated as the areal average of absolute geopotential height error (m) between analyses and forecasts at specified pressure levels. Derived data from radiosondes released at Meiningen, Germany 4 times a day every 6 h will be compared to model profiles to determine the trajectory errors the forecasts could impose on artillery.

3. Results and Discussion

Tables 1 and 2 display the model error growth for cases Andrea and Joachim, respectively. Levels of interest are 850 hPa (mb), which represents low-level flow near the top of the planetary boundary layer, 500 hPa (mb), which is the mid-tropospheric wind, and 200 hPa (mb) near the upper tropospheric jet core. It can be seen that GFS analysis and forecast data is unavailable for the period that corresponds to hour 18 during the integration (1800 UTC 05 January 2012) due to issues with the GFS model itself and so has been left out of the table.

Table 1. Areal-averaged absolute height error (m) for designated pressure surfaces valid 05 January 2012 forecasts with respect to GFS analysis.

Level	Hour	GFS	LG	MD	SM
850 hPa (mb)	0	0.00	0.95	0.95	0.95
	6	6.52	11.71	9.48	6.95
	12	8.83	10.26	9.47	9.83
	24	9.74	24.58	18.08	14.41
500 hPa (mb)	0	0.00	1.92	1.92	1.93
	6	7.22	9.40	8.61	7.77
	12	10.72	12.70	11.14	11.14
	24	12.74	19.08	14.91	13.96
200 hPa (mb)	0	0.00	8.44	8.45	8.44
	6	6.27	8.58	9.92	8.24
	12	11.09	12.86	15.18	14.52
	24	13.92	17.47	16.38	14.77

Table 2. Areal-averaged absolute height error (m) for designated pressure surfaces valid 16 December 2011 forecasts with respect to GFS analysis.

Level	Hour	GFS	LG	MD	SM
850 hPa (mb)	0	0.00	1.19	1.19	1.19
	6	3.83	6.32	5.60	3.80
	12	6.09	9.30	8.59	6.46
	18	11.74	25.15	21.10	13.11
	24	26.28	45.50	41.30	32.58
500 hPa (mb)	0	0.00	1.76	1.76	1.76
	6	5.87	6.03	6.01	4.97
	12	8.25	10.54	9.99	8.88
	18	13.83	23.82	19.49	13.74
	24	20.88	31.73	28.53	20.80
200 hPa (mb)	0	0.00	7.57	7.57	7.57
	6	7.90	6.81	6.76	5.20
	12	11.90	11.04	10.04	9.70
	18	8.76	11.80	12.49	12.39
	24	7.68	10.50	10.32	11.56

In both cases clear trends are evident. Initially, both GFS forecasts and analyses are equal but small differences between the GFS analysis and WRF exist at all levels. The magnitude of initial error increases with height from around 1.0 m at 850 hPa (mb) to 7–9 m at 200 hPa (mb). These initial differences (m) are approximately equal to two decimal places for all WRF experiments and appear to result from interpolation from the coarse GFS 0.5° grid to the WRF 9 km grid. This difference then grows with time as errors between the GFS analysis and forecast appear at hour 6 as well. Overall, there is less difference from the GFS than WRF, which may in part be due to model physics, underlying topography, and land/sea interface differences between models with different resolutions. As suggested by past research the smallest WRF domain has the lowest difference, closest to the GFS forecast difference due to the strong control the forcing data has on such a limited area domain. As the domain size grows, so does the error relative to the analysis. Regardless, this would suggest that the 0.5° GFS outperforms any WRF simulation.

Graphically, the differences in the forecasts are not as apparent as seen in figure 2. It is clear that the WRF forecasts follow the driving GFS forecast field closely, and all the forecasts have similar differences from the analysis field. The WRF forecasts are tightly grouped in most regions and in some places coincident, revealing that there is little spread despite the range in domain sizes. Also, due to grid resolution of the data (0.5°~50 km versus 9 km), the GFS data is smoother than the WRF data that may contain the effects of gravity waves due to LBCs, model instability, and/or terrain, which creates larger differences that are sometimes significant. This added detail within the WRF forecasts due to greater spatial resolution appears to be responsible for the greater difference with the analysis than is found with the more coarse GFS forecast. Whether this is a numerical artifact of LBCs, numeric instability, or physical reality due to topography is unknown.

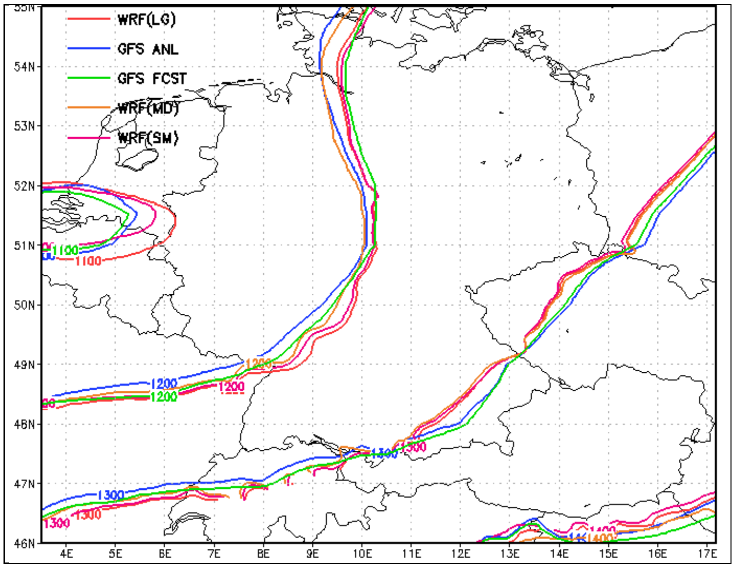

Figure 2. Height contours (m) on 850 hPa (mb) pressure surface valid 0600 UTC 16 December 2011.

A more detailed analysis focuses on the results at Meiningen, Germany, the center of the area of interest, which represents the artillery trajectory mid-point. Model profiles are compared against observed soundings for the 6 h and 12 h forecast times. Fields of interest are pressure (or geopotential height), temperature, relative humidity (RH), wind speed, and wind direction. From pressure, RH, and temperature we calculate the density of the moist atmosphere that creates drag on projectiles. The wind speed and direction are used to determine the flow that the projectile will be subject to in its trajectory towards the target area. The most critical level is near the apex when the projectile is moving slowest and is most susceptible to environmental winds.

The wind profiles in figure 3 display large differences between the models and observations below 500 hPa (mb) but agree better at upper levels. Boundary-layer winds are overestimated by 10–15 ms^{-1} (20–30 kts) in the 900–850 hPa (mb) layer. This overestimation disappears above the boundary layer briefly but then appears again in the layer between 700–600 hPa (mb). In both cases the driving GFS data would appear to be responsible for the WRF overestimation as well, but in the boundary layer the difference in parameterizations may have caused the WRF to increase the winds even further.

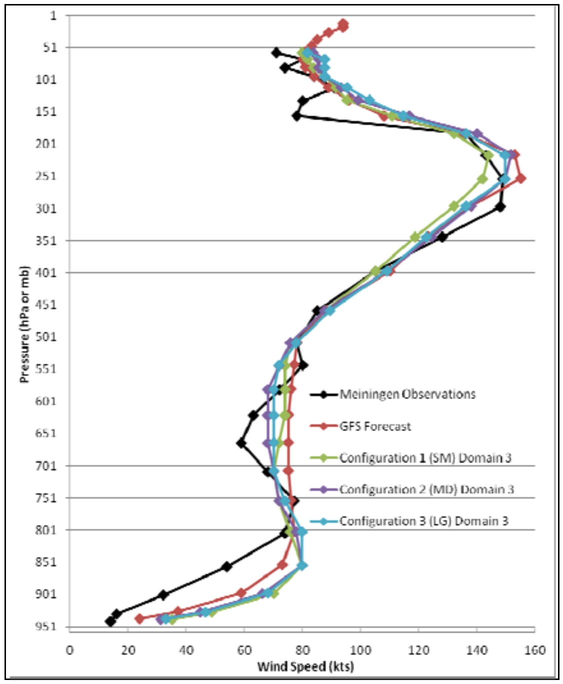

Figure 3. Wind profiles at Meiningen, Germany valid 0600 UTC 05 January 2012.

At 500 hPa (mb) and 200 hPa (mb) the models are in close agreement with observations as seen from the low-vector wind differences (ms^{-1}) in table 3. The 1 km grid (D3) within the smallest parent domain (SM) produces the lowest vector wind difference at 200 hPa (mb) and second lowest at 500 hPa (mb) but the highest at 850 hPa (mb). An interesting feature is also the high-vector wind difference produced by the intermediate nest (D2) at both 200 and 500 hPa (mb), whereas the parent domain (D1) at these levels is closer to the smallest nest (D3) in all experiments. At 1200 UTC, the SM experiment has the lowest vector wind difference at all levels and in all domains than other WRF experiments and the GFS as well. Density near the surface is most critical and subject to large variations because of water vapor. At 0600 UTC, all WRF experiment and domain results show improvement over GFS density, however, at 1200 UTC only the D3 from all experiments is close to or shows improvement over the GFS.

Table 3. Density and vector wind differences (ms^{-1}) for Meiningen, Germany model soundings valid 0600 UTC and 1200 UTC 05 January 2012.

6 UTC	**ρ_{850}(kg/m^3)**	**200 hPa**	**500 hPa**	**850 hPa**
GFS	0.0064	6.82	1.57	11.47
SM(D3)	0.0053	3.64	1.19	16.71
MD(D3)	0.0051	4.96	2.94	15.58
LG(D3)	0.0051	3.74	0.80	15.58
SM(D2)	0.0011	3.64	1.13	14.69
MD(D2)	0.0017	4.96	2.94	13.85
LG(D2)	0.0017	3.74	1.92	14.93
SM(D1)	0.0012	4.60	1.62	14.34
MD(D1)	0.0024	4.96	2.75	14.78
LG(D1)	0.0038	4.68	1.58	15.09
12 UTC	**ρ_{850}(kg/m^3)**	**200 hPa**	**500 hPa**	**850 hPa**
GFS	−0.0030	5.11	4.64	3.74
SM(D3)	−0.0033	4.99	3.96	2.50
MD(D3)	−0.0020	6.26	6.82	4.46
LG(D3)	−0.0002	7.36	5.79	5.80
SM(D2)	−0.0057	4.80	4.11	2.63
MD(D2)	−0.0057	5.42	5.85	3.97
LG(D2)	−0.0037	7.36	6.38	5.53
SM(D1)	−0.0055	4.80	3.59	4.47
MD(D1)	−0.0041	5.15	5.96	4.67
LG(D1)	−0.0030	7.14	5.16	3.97

4. Summary and Conclusions

To isolate the impacts of lateral boundary conditions a series of experiments were performed with WRF-ARW using different parent domain sizes. The model experiments were centered over Meiningen, Germany for two strong synoptic forcing cases during the winter of 2011–2012. It was anticipated, based on past research, that the most accurate results would be produced from a larger domain size because the larger domain would facilitate greater ”spatial spin-up” and allow the model to diverge from its initial forcing field.

Experimental WRF results displayed sensitivity to domain size. Model error, compared to GFS analysis was found to be a function of domain size with lowest model error from the smallest domain size. The smallest domain forecasts had comparable error to the GFS forcing field. Meteorological trajectory calculations provided more detailed information for the artillery ”target area.” Relative to observations the inner-nest produced the lowest combined vector wind and density differences from observations at forecast hour 12, whereas improvement among experiments was more varied at only forecast hour 6.

Results suggest that the initial forcing field provided by the GFS 0.5° forecast offered high-quality initial and lateral boundary conditions that did not introduce substantial errors. Given the quality of the forcing field it is not surprising that the smallest WRF domain has similar model error to the GFS forecast. There was no added benefit to increasing the parent domain size in these strong forcing cases. It may be that the parent domain was not increased sufficiently to show sensitivity; however, given the results, increasing the size further will not likely improve model performance.

Further testing should be conducted prior to a choice being made on the operational configuration for the U.S. Army and Marine artillery model. Experiments for quiescent cases where local surface forcing is dominant are necessary. Past research suggests that larger domains are more favorable under such conditions. Data assimilation should be applied for the cases studied here and subsequent quiescent cases. Data assimilation should reduce model error growth and improve trajectory calculations. Different PBL schemes should be tested to determine what effect they have on the low-level vector wind differences found in the analysis of the meteorological trajectory calculations seen at 0600 UTC 5 January 2012. The errors at this time may be within the model spin-up time however and have little to do with model physics.

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List of Symbols, Abbreviations, and Acronyms

3DVAR	3-Dimensional Variational data assimilation
AMS	American Meteorological Society
FDDA	four-dimensional data assimilation
GFS	Global Forecast System
LAMs	Limited area models
LBCs	lateral boundary conditions
LG	large
MD	medium
MM5	Mesoscale Model 5
NCAR	National Center for Atmospheric Research
NWP	numerical weather prediction
QNSE	quasi-normal scale eliminate
RAMS	Regional Atmospheric Modeling System
RCM	Regional Climate Model
RegCM3	Regional Climate Model 3
RH	relative humidity
WRF-ARW	Weather Research and Forecasting Advanced Research WRF
WSMR	White Sands Missile Range

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